Tailoring the Prototyping Process to Achieve Customer Value

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ABSTRACT

The main objective for prototyping is to get the most value out of the opportunity. Value may take the form of information, performance, displaying production readiness or proving capability for the amount of resources consumed and time required. The extents to which the aforementioned variables add customer value differ from project to project. Therefore, it is important to understand what the customer values most in the effort and modify the process to best achieve the prioritized results.

Achieving customer value in the prototyping process is critical to Raytheon's Advanced Products Center (APC) business because it is likely that the customer will bring production into the facility. Misalignment with customer expectations will be avoided by tailoring the process around the metrics that the customer prioritizes. Confusion and inconsistency will be limited by having a clear and understood process. The intent of this thesis is to provide a means of tailoring the process to best achieve customer value given the characteristics of the project.

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1. Introduction and Background

Raytheon's Advanced Products Center (APC) produces complex microwave assemblies used in Active Electronically Scanned Array (AESA) radar systems. APC is part of the Space and Airborne Systems (SAS) division of Raytheon. SAS designs and manufactures complete AESA radar systems and is an internal customer to APC.

Business comes into APC in a couple of ways. Sometimes, customers will employ APC to provide both the design and manufacture of microwave assemblies. In this case, design teams within APC will work with the Microwave Automated Factories (MAF), one of the production units within APC, to design and manufacture the assemblies. Other times, customers will generate a design and turn to the MAF to produce the parts.

Internal customers are often very satisfied with the quality of production that the MAF provides. The MAF has incentive to optimize the manufacturing process as early as possible in order to achieve high throughput and yields, which lead to profit. However, there are customers within SAS that have voiced concerns regarding the task of prototyping with the MAF. During prototyping, the MAF and customer often are not aligned regarding the expectations of the effort. One such misalignment occurs when the MAF works to generate a more robust process and deliverable than was expected by the customer. The negative effect is that this effort requires more time than the expected effort, which leads to dissatisfaction. Due to a number of misunderstandings such as these, many internal customers are pursuing external suppliers for their prototyping needs.

1.1. Business Effects of Losing Prototyping Business

The business effect of losing prototyping business for APC can be quite substantial. The most direct effect is the loss of revenue that would be generated by the prototyping business. Two indirect effects have an even greater impact on the business. First, the MAF is far more likely to win production contracts when they produced the prototypes for the project. By losing prototyping business, the MAF is vulnerable to losing business that they would otherwise have obtained. Second, when production business does come to the MAF when parts are prototyped elsewhere, the MAF has lost an opportunity for learning about the process during the prototyping phase. Therefore, more effort must be made in the production effort, which may reduce profit from the projects.

Another effect of prototyping occurring outside of the MAF is that when production is brought in, possible redesign might be required in order to become compliant with the MAF's capabilities. If parts are designed and prototyped with the MAF in mind from the beginning, redesign of this nature would not be necessary. Although the financial implications in this circumstance do not necessarily impact APC, it will have a major impact on the internal customer. In a study of two similar projects in the past, it was estimated that the development cost for the project in which this scenario occurred was twice that of the equivalent program developed in the MAF from the beginning.

1.2. Defining the Prototyping Effort

The goal of a prototyping effort is to get the most value for the effort put in. The value can take the form of information, display of performance, winning a contract award, or achieving production readiness. There is often a discrepancy between what the design team and production team consider to be most important on a prototyping effort. Additionally, the customer prototype expectations are not always well communicated and understood.

Defining the prototyping effort up front, such as communicating the priority of the associated goals and identifying the tasks that will be performed, will lead to a focused effort that will add value in the eyes of the customer. The intent of this thesis is to propose a methodology that Raytheon can use to tailor their prototyping process based on the prioritized goals and environment of the prototyping effort. The methodology described later in this thesis will describe how these goals and characteristics will be evaluated and used to decide how to tailor the process tasks.

1.3. Raytheon Company

Raytheon, NYSE: RTN, specializes in defense, homeland security, and other global government markets. Raytheon employs 72,000 worldwide and achieved 2007 sales of $21.3 billion. The company is "Aspiring to be the most admired defense and aerospace systems supplier through world-class people and technology." Innovation is a key driver to the success of the company, as it seeks to develop new products to serve its customers (Raytheon, 2008).

1.3.1. Space and Airborne Systems

Raytheon Space and Airborne Systems is a leading provider of advanced and integrated sensor systems. Key capabilities of SAS are airborne radars and processors, electroptic/infrared (EO/IR) sensors, electronic warfare and precision guidance systems, active electronically scanned array (AESA) radars, space and missile defense technology, and intelligence, surveillance, and reconnaissance (ISR) systems. SAS, headquartered in El Segundo, earned revenues of $4.3 billion and employs 12,000.

1.3.2. Advanced Products Center

The Advanced Products Center (APC) specializes in RF/Microwave technology. They have design, development, and manufacturing capabilities that support many of Raytheon's critical initiatives including missile, radar, and communications. APC provides engineering expertise and optimized factory design in order to provide high yield and low cost solutions.

APC desires to be the best option for manufacturing complex microwave assemblies. The production area of APC, the Microwave Automated Factories (MAF), contains cutting edge equipment that is capable of providing industry leading products. Design producibility is a significant goal for APC. Design guidelines have been developed to encourage use of best practices along with common processes, designs, and materials in order to provide advantages in process development, production throughputs and yields.

Providing quality prototyping services is an important means for the MAF to acquire future, profitable production business. The MAF has a great deal of prototyping resources. Manual assembly capability consists of universal equipment that can be operated by a small number of highly trained individuals. This production option allows for high flexibility and low investment and setup cost. The MAF also possesses a Product Design and Development Line (PDDL) that contains specialized equipment dedicated solely to pre-production activities. This production method allows for high precision operation without requiring in-depth operating instructions and process control. Also, prototyping activities may take place on the production equipment. This production method allows the highest degree of process verification, giving information regarding how well the parts will be able to transition into production.

2. Literature Review

This section will discuss the importance of establishing processes as well as the necessity to tailor processes based on the particular circumstances in which the process is performed. Various aspects of prototyping will be discussed, such as the purposes for prototyping and prototype planning. The main themes from the review will be highlighted, as will a brief description of how these themes will be leveraged in providing a methodology for tailoring the prototyping process for the MAF.

2.1. Business Processes

Michael Hammer (2001) describes a process as "an organized group of related activities that together create a result of value to customers." This definition implies that tasks are merged purposefully, while consisting of all necessary activities and excluding unnecessary activities. The activities are aligned in order to meet the overall purpose of the process, the output that is valued by the customer. According to Hammer, customers, results, and processes must be focused on simultaneously. Results directly depend upon the process that takes place.

2.1.1. Importance of a Process

Processes are important in general because they lead to better execution. A well planned process identifies what will be done, by whom, and in what order. Implementing a process will lead to repeatable, consistent and predictable results. By identifying and following the best known process, costs will be reduced, quality will be improved, and lead time will be decreased. For instance, employees will know up front the work that they are expected to do, and therefore will not waste time identifying what work to do next. Additionally, by performing tasks consistently, organizations are able to learn about the process more quickly and are able to improve upon its best practices (Hammer, 2001).

2.1.2. Difficulties of Processes

A major difficulty for many businesses regarding processes is that the organization is structured functionally. Processes typically cover multiple functions, and due to functional silos, inefficiencies exist around the handoffs between these departments. Often, individual departments perform work within a process with little knowledge or interest in parts of the process outside of their narrow focus. This behavior may lead to positive results on the sub-process but will typically provide sub-optimal results for the process in its entirety.

Processes are often legacies or artifacts that at one time made since for the organization. As situations change, it is necessary to monitor the effectiveness of the process and tailor it accordingly. Often, workers will simply deviate from the process in order to get things done in the new environment, rather than propose that the process be updated. By sidestepping the process, employees are constantly improvising, one of the main goals for which the process was designed to prevent in the first place.

Another occurrence that leads to ineffective processes is an additive effect. When management witnesses a problem on a particular project, they often act to add a check or prevention to the overall process. This form of action might seem beneficial; however it is possible that the process will become an accumulation of preventative measures against any item that has gone wrong in the past. Very likely, after all of these incremental additions, the process will no longer concentrate on the main value added tasks that create customer value.

2.1.3. Process Reengineering

Michael Hammer has performed extensive research on the importance of processes in business and encourages organizations to "Reengineer" their business around processes. He advises that companies first identify the core processes that lead to the fulfillment of customer value. Typically, each of these core processes will involve tasks performed by personnel from numerous functions within the business.

Hammer suggests assigning an owner for each entire process. By having a single point of responsibility for a process, there will be incentive and accountability for optimizing the process as a whole, thereby addressing handoffs, communication between groups, and redundancy. Goals and performance metrics should measure the success of the entire process from start to finish, thereby encouraging team work and cooperation.

In order to achieve high performance, Hammer claims it is important to specify how tasks fit together. Much of the inefficiency in business processes occur at handoffs within the system. Addressing how work is handed off from person to person will lead to significant gains.

A number of tasks and processes are performed simply due to historical reasons which may no longer be applicable. Taking an end to end look at a process, it will be easier to identify unneeded or sub-optimal tasks and replace them with relevant tasks or eliminate them altogether (Hammer, 1993).

2.1.4. An Example of Successful Process Reengineering

Progressive Insurance made a remarkable transformation of its company's operations. Progressive deviated from the well established and accepted procedures that existed in the long established auto insurance industry. By restructuring its processes to best meet the needs of its customers, Progressive gained market share and has grown its revenues from $100 million in 1980 to approximately $6 billion in 2000 (Hammer, 2001). This accomplishment is most notable because it took place in an industry that was only growing at a rate around 3-4%.

Progressive's "Immediate Response" approach set a target that each vehicle would be seen by an adjuster within 9 hours of notification from the customer, compared to the industry average of 7-10 days. Additionally, when feasible, the adjuster will produce an estimate and provide payment to the customer right away.

To achieve such drastic improvements, all that was needed was a process designed to meet the overall needs of the customer. Progressive realized that there were unnecessary tasks, handoffs, and delays. By removing waste from the process, Progressive was able to become more profitable, lower prices, and increase customer satisfaction.

2.2. Tailoring Processes In Product Development

Processes often need to be tailored in order to meet the conditions of their environments. As Edward G. Krubasik (1988) states in his report titled "Customize Your Product Development," "One size doesn't fit all." The tasks performed, the rigor with which tasks are performed, and the management approach taken for a process all depend on the context. The following sections will examine how certain factors have been analyzed and used to shape product development processes.

2.2.1. Flexibility: A process mirrors uncertainty

Alan MacCormack (1999), associate professor in the Technology and Operations Management area at the Harvard Business School, offers two propositions regarding flexibility under uncertainty in the product development process. First, firms in industries that contain higher levels of uncertainty adopt more flexible processes than do firms in industries with lower uncertainty. Second, MacCormack proposes that individual projects facing more uncertainty will adhere to a development process with higher flexibility than projects facing lower levels of uncertainty.

MacCormack refers to flexibility as the proportion of the window of opportunity, the time from the start of the project until design freeze, to the total lead time of the project. Conceptually, it is logical that projects and industry facing uncertainty would want higher levels of flexibility in order to respond to new information that may shift the direction of the project.

A field study was performed to investigate this theory. The server and software industries were studied and compared to automotive industry data. Using intuitive means along with stock beta values, the industries were grouped into uncertainty levels, with automotive being lowest, servers middle, and software highest. Results of the study showed the following flexibility:

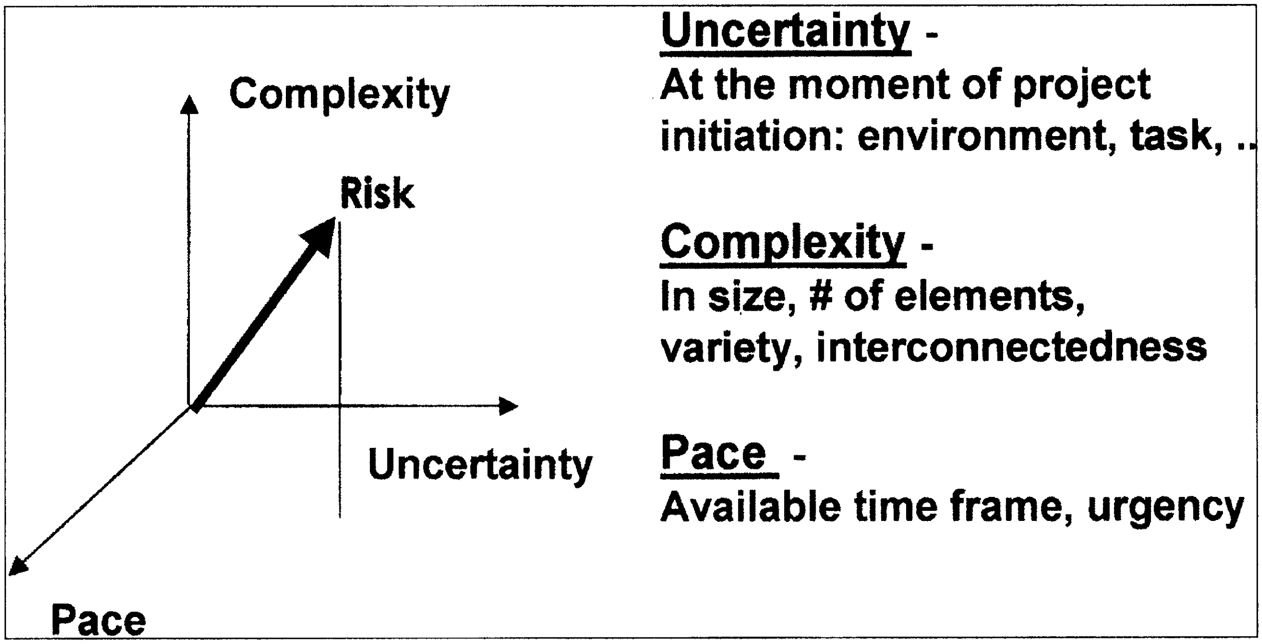
- Automotive – 39%

- Server – 64%
- Software – 78%

The empirical results support the claim that firms in uncertain fields desire more flexibility than those in less uncertain fields.

2.2.2. The UCP Model (Uncertainty, Complexity, and Pace)

Dov Dvir, Aaron J. Shenhar, and Shlomo Alkaher (2003) claim that "a proper identification of project characteristics and adaptation of a suitable style is critical for success." Their study and development of the UCP Model demonstrates that project complexity and pace, in addition to technological uncertainty, should be considered when determining project management style. Although many companies vary their process, there rarely is an explicit effort to classify the project up front based upon these project characteristics. The UCP model is shown graphically in Figure 1.



Uncertainty -
At the moment of project initiation: environment, task, ..

Complexity -
In size, # of elements, variety, interconnectedness

Pace -
Available time frame, urgency

Figure 1: The UCP Model

Technological uncertainty, as in MacCormack's work, is a major input into the UCP model. The model groups projects into four types of technological uncertainty: Low-Tech, Medium-Tech, High-Tech, and Super High-Tech. As the level of technology rises, so does the technological uncertainty, and thus the risk associated with the projects. The more innovation involved in the product, the later design freeze must be in order to leave room for changes as information becomes available. In general, with increased uncertainty, the product development process and management style must be more flexible.

The UCP Model also points out how project complexity affects management style and processes. The model uses a hierarchal framework to look at levels of scope. The three complexity levels presented in the model are Assembly Projects, System Projects, and Array Projects. Project size, number of elements, variety, and interconnectedness increase as complexity increases, thereby increasing the amount of risk associated with the project. In addition to the organizational hierarchy contribution, project complexity will increase based on the complexity of the product itself.

The third element that makes up the UPC model is pace. Pace primarily considers the relative amount of time to complete the project, the importance of projects meeting the given time schedule, and the consequences of not being on time. Regular projects typically have a schedule for completion, but missing the deadline is not terribly critical and is typically tolerated. Fast/Competitive projects typically have success strongly tied to time to market. Missing the projected schedule will lead to lowered competitiveness, including profit loss and damaged competitive positioning. However, missing the deadline for these projects is not considered fatal. Critical/Blitz projects demand urgency, and it is imperative that these projects not suffer delays. Delays on these projects lead to project failure.

Dvir, Shenhar, and Alkaher's case study on an Israeli defense project concludes that the success of the project was limited due to the incorrect classification of the project type and incorrect adaption of managerial style at the start of the project. The project's technological uncertainty and scope were underestimated, and as a result, the processes followed were not optimal for the risk and context associated with the project. By analyzing the project characteristics up front and aligning the process accordingly, appropriate project execution will be facilitated.

2.2.3. Crash Program or Perfect Product

A tradeoff must be considered when tailoring a product development process (Krubasik, 1988). There is an opportunity cost associated with missing proper timing on a product introduction. Opportunity costs may include loss of market share, total loss of business, or any other penalties of delivering a product late to market. Also, there is an entry risk associated with going to market with a wrong or suboptimal product. The relative importance of both of these risks will vary from project to project. Therefore, these risks should be considered when architecting the process. However, Krubasik states in his special report, "Customize Your Product Development," that managers often act with the same development strategy for every project rather than considering the context of the project.

A crash program is appropriate for situations where the opportunity cost is high in relation to the entry risk. A crash program tailors its process such that activities are performed to concentrate on speed rather than reducing risk. For example, IBM used a crash program strategy when entering the PC industry. Due to competitors gaining market share, it was vitally important for IBM to get to market quickly. Additionally, development costs were rather low compared to IBM's size. Therefore, the crash program made since in this case. IBM made decisions, such as outsourcing major components, which reduced the development time. Of great interest to this work, IBM tailored its product development process down from the eight stage formal product planning approach to one that allowed quick decisions with little interference.

Situations where the entry risk is high compared to opportunity cost, the program style should aim to produce a perfect product. For example, when launching a new line of aircraft, it is much more important for Boeing to get the product as close to perfect as feasible. The landscape of the airline business is such that a delay to market will be insignificant compared to the enormous expense of launching a vast product that has imperfections. A graphical representation of product development styles given opportunity cost and development risk is presented in Figure 2.

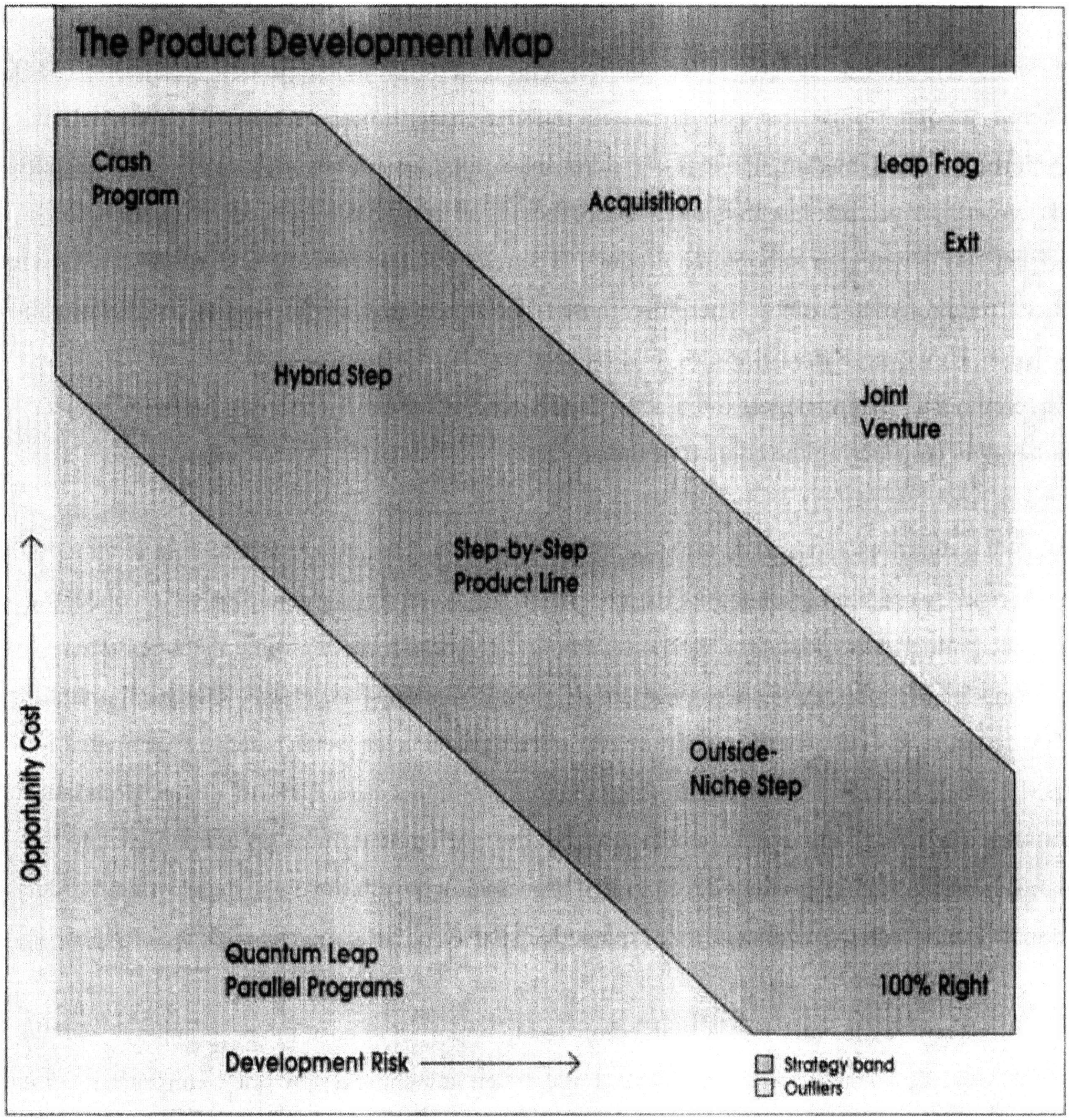


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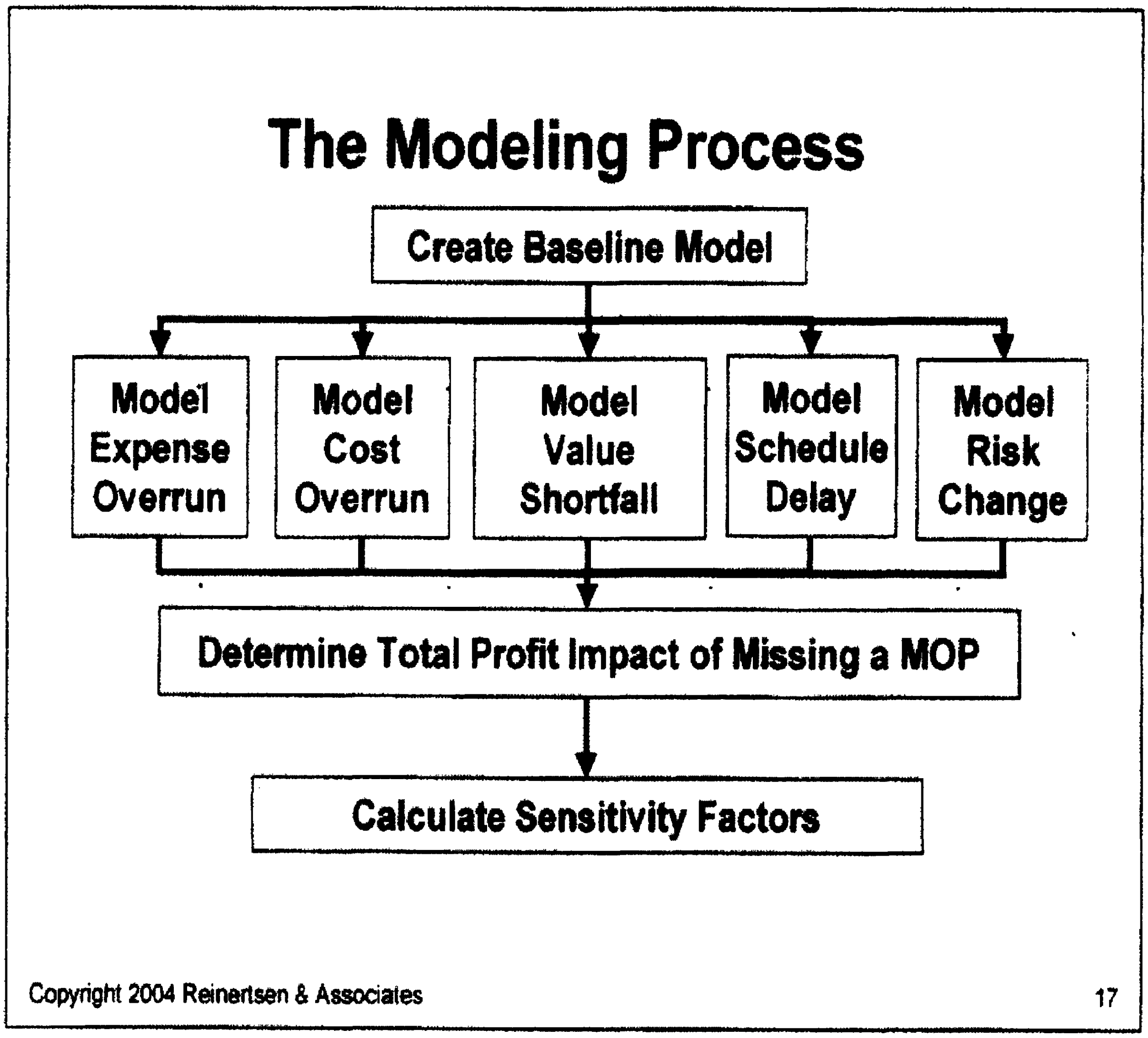
Figure 2: Product Development Map

2.2.4. Economic Objectives of Product Development

Five economic forces can be used to determine priorities in the development process: development cost, development schedule, product unit cost, product value, and risk. Don

Reinertsen (2004), President of Reinertsen and Associates consulting firm specializing in product development processes, proposes a modeling process that examines the effects of overruns or shortfalls in the economic forces listed above on the total profit of a project, as shown in Figure 3.



The Modeling Process

Create Baseline Model

Model Expense Overrun

Model Cost Overrun

Model Value Shortfall

Model Schedule Delay

Model Risk Change

Determine Total Profit Impact of Missing a MOP

Calculate Sensitivity Factors

Figure 3: Product Development Economic Factors

From this information, sensitivity factors are calculated and compared in order to determine the major drivers of the projects financial success. Economic forces with high sensitivity factors should be monitored more closely than those with lower sensitivity factors.

2.3. Prototyping

Ulrich and Eppinger (2004) define a prototype as "an approximation of the product along one or more dimensions of interest." The forms of prototypes range from concept sketches to fully functional versions of the product. Four purposes of prototypes are discussed, in addition to prototype planning.

2.3.1. Four Purposes of Prototypes

Four purposes for which prototypes are used are learning, communication, integration, and milestones (Ulrich, 2004).

Learning
Prototypes provide knowledge regarding whether or not the product will work as well as how well it addresses the needs of the customer. The information collected can then be used to improve upon the existing design and add new features to better serve the customer.

Communication
Prototypes provide communication to all concerned parties in the product development process, including customers, vendors, team members, and management. Physical prototypes, in particular, make the concept of the product easier to grasp. As a result, the customers are able to provide valuable feedback regarding their perception of the product.

Integration
Prototypes are used to ensure that the various components of a product interface properly with each other and operate as a whole. Any problems with the combination of components are identified during prototyping, allowing the different members of the product development team to coordinate and resolve any issues. Additionally, prototypes help to bring members of the product development team together on the same page and ensure agreement on the product's design.

Milestones

Prototypes signify the achievement of a certain level of performance and functionality. They demonstrate progress towards the end product. In many cases, especially in contracts with the government, a prototype is needed prior to approval to continue with product development.

2.3.2. Prototype Planning

Planning for prototypes is important in order to avoid what Clausing (1994) terms as the "hardware swamp." Prototyping efforts that take place without a well thought out plan can lead to wasted efforts that do not provide meaningful knowledge. A four-step method for planning the prototyping effort in order to achieve beneficial results includes defining the prototyping purpose, determine the level of approximation, outline an experimental plan, and create a schedule for procurement, construction, and testing (Ulrich, 2004).

Define the Prototyping Purpose

In this step of prototyping, the team determines what needs to be learned and accomplished during the prototyping effort. The final use of the prototype is considered as well as integration with any larger systems. Any milestones within the greater product development process are considered here.

Determine Level of Approximation

The team next determines the simplest type of prototype that serves the purpose stated above, including making use of an existing prototype. It is at this step that the team identifies what form the prototype should take and how robust of a prototype is needed.

Outline an Experimental Plan

This step outlines the variables that the prototyping effort intends to experiment. Additionally, the means for testing these variables is determined. Also, the team determines how they will analyze the results.

Create a Schedule for Procurement, Construction, and Testing

The prototyping activities are scheduled based on three primary dates. The first date determines when all parts should be prepared to be assembled. The second date is the time when the first part will be tested. The third date is when all testing will be completed and results are summarized.

2.4. Literature Review Themes

Use of processes leads to better execution. Employees know what to do and when, therefore preventing the need to invent the process every time as they go. Additionally, major gains can be achieved by reengineering business processes to obtain customer value. By placing someone responsible for the entire process, inefficiencies that occur during handoffs can be identified and eliminated. Tailoring processes is often necessary in order to best meet the needs of the given environment. The context and goals of a project should drive the type of activities that take place within a process. Uncertain environments require processes to be more flexible. Economic objectives differ from project to project, and the process needs to account for the priorities of the particular project. For example, environments where time to market is crucial need a crash program to achieve results quickly, while other environments dictate that the product be perfected prior to completion.

Prototypes have a number of purposes, such as knowledge, communication to all concerned parties, integration with other components, and signaling communication of milestones. In order to ensure that the purpose of the prototype is obtained as efficiently as possible, it is useful to have a prototype plan. Steps included in the plan are defining the prototyping purpose, determining the level of approximation, outlining an experimental plan, and creating a schedule for procurement, construction, and testing.

During my internship, I looked to build upon these themes in the context of prototyping at the MAF. I researched the defined prototyping process and observed the actual prototyping process. In the case of the MAF, having clear and understood processes will remove inconsistency in the personnel involved, the manner in which prototyping is performed, and the criteria under which decisions are made. Also, by designing the process around customer value, each prototyping effort in the MAF will be performed with the customer's wishes in mind.

I investigated the different purposes of prototyping efforts and examined how different types of prototypes were considered. Also, I looked into what factors influenced prototype development, and looked for ways that the process may vary. With this in mind, I worked to provide a range for the different characteristics of a given prototyping effort and to develop a system for altering tasks in the process given these characteristics. Prototyping efforts in the MAF will be most successful when they are tailored to achieve the prioritized results of the customer and to match the environment in which it is produced.

3. Methodology

This thesis is based on a combination of a literature review and an internship performed for the Raytheon Company. While working with people during the internship at Raytheon, I analyzed the reasons for the loss of prototyping business. I interviewed several people in order to get a sense of the issues the MAF was facing. With the assistance of many people at APC, I developed prototyping guidelines for the MAF, addressing key issues that I had observed and that were brought to my attention during the interviews. Also, I referenced literature regarding processes and prototyping, described in Section 2, in order to benchmark current solutions to similar issues.

As a student in the Leaders for Manufacturing (LFM) program at the Massachusetts Institute of Technology, I performed a 6.5-month internship for Raytheon, one of the program's partner companies. During the internship, I analyzed the prototyping process at the APC facility, paying close attention to factors that affected the cycle time of prototype development. I worked directly with the RF Packaging Processes group that was primarily responsible for the development, implementation, and improvement of packaging and assembly methods for producing microwave assemblies.

I first looked into the current state of the prototyping process. I joined a cross functional product development team that was currently working on a prototyping effort in order to observe the activities that were taking place and the decisions that were made. Also, I looked at existing program data, such as progress reports, budget and spending reports, and gate reviews in effort to develop a baseline for prototype development schedules. Most of the data that I found was at a high level, and it was difficult to derive data for specific tasks within the process. Labor reports typically contained a large amount of work under one billing number. Project reports would contain major milestones and high level timelines, but detail regarding task times was limited.

In order to leverage the knowledge of individuals working within the prototyping process, I informally interviewed a number of individuals regarding projects they had worked on as well as general issues and opinions that they had regarding the process. Individuals interviewed include program managers, process engineers, design engineers, purchasers, material handlers, manufacturing engineers, and customer representatives. I asked a wide range of questions concerning things gone well, opportunities for improvement, and memorable occurrences for projects they had worked on. Additionally, I asked for the prototyping tasks that these individuals performed, and in what cases each of the tasks are performed. Also, I obtained estimates for the range and average amount of time each of the tasks demanded. This data would later be used to show the impact that properly tailoring the process would have on prototype delivery time.

One major issue was that there were not formal instructions regarding how the MAF should perform tasks during a prototyping effort. With the assistance of my supervisor, I formed a cross functional team that would collectively provide input on how the prototyping process should be performed. Through group and individual meetings, our group developed the "MAF Prototyping Guidelines," which described how the prototyping process should be performed. I later compiled the guidelines, obtained the appropriate approvals, and incorporated the guidelines into the MAF documentation system. The guidelines will be discussed further in section 4.3.

4. The MAF Prototyping Process

A look into the current MAF prototyping process is important in order to identify the key issues that are leading to poor customer satisfaction. A major consideration with the current process is whether or not APC will be performing the design activities. Often times, customers will come to the MAF with a design, and simply ask the MAF to build to print. This process may be carried out with as few as one person, involve minimal tasks, and require a minimal amount of time to complete. On the other extreme, APC may be called on to develop the design and the physical prototypes. In this scenario, often a cross functional team of ten or more employees will be formed. Action items are typically added during meetings as new needs arise.

Some of the key issues with the current process were that there was inconsistency in the way tasks were performed, there was not a formal means of classifying different types of prototypes, and there was not a defined way to tailor the process to meet specific prototyping needs. However, the MAF has done some things very well in order to meet aggressive time schedules which can be leveraged for future successes. With practices such as these developed with the Raytheon team, a proposed process was developed during the internship project. This process is discussed at the end of this section.

4.1. Issues with the Prototyping Process

Prior to the internship project, there was inconsistency in the way many tasks were performed within the prototyping process. For instance, there was not a primary contact for customers to go to with a set of prototyping needs. A design team from the SAS El Segundo site might have been familiar with a test engineer and have decided to contact him regarding some work they had planned. The test engineer was more than happy to help but was not trained to ask all the proper questions regarding what, in addition to testing, the prototyping effort was to consist of. Additionally, he or she may not know whom to notify. The success of the project may hinge on what people within the MAF facility are contacted and when.

The MAF did not formally address the different purposes of prototypes, nor did the MAF discuss the different processes to achieve these various prototype purposes. The behavior that developed tended to be a one size fits all approach. Since the MAF is tightly controlled by production, concentration is often on robust, production processes. This production mindset, along with the one size fits all approach, led to poor results for quick early stage prototyping, although it may have led to successful late prototype and early production efforts.

In a similar fashion, there was inconsistency in the performance of the prototype process. The MAF is very customer focused, and each program would do things differently in order to respond to requests from the customer, thereby limiting the amount of process rigor. Alternatively, decisions regarding how to perform various tasks would often be made based on individual preferences or considerations rather than the customer's best interests. One example involves a process engineer that had previously witnessed a situation where a proof of concept prototype was requested and delivered, where the intent of the effort was to provide a quick prototype for test purposes rather than develop the manufacturing process. However, upon receipt of the prototype, the customer requested that the part be put into production quickly, although a high volume process had not been developed. On future projects, this engineer had incentive to develop highly robust processes despite a customer's need for a quick prototype. The incentive was that the MAF would be better prepared for potential production requests from the customer in the future. The downside to this decision is that the original prototype will be delayed due to the additional effort put in on the original process.

Many of the designs coming from customers lacked producibility elements that would have been beneficial for producing a timely, cost effective prototype. For instance, the design may require new manufacturing processes, new test equipment, or materials that have not been tested by the MAF. As a result, additional time and resources are necessary to provide these prototypes.

Scope creep and late design changes were a common cause for schedule delays. Customers would often change designs or carry TBD characteristics late into the development process. Interviews with personnel at Raytheon reveal that when these changes were made, APC and the MAF were reluctant to push back and communicate the negative effects to the customer. The reluctance to push back seemed mostly to be an effort to achieve high customer satisfaction regardless of the situation.

4.2. MAF Prototyping Successes

The MAF has had a number of successful efforts to meet aggressive prototyping needs. Some examples of techniques used to meet tight schedule requirements include strategic design and component reuse, retrofitting existing test equipment and software, and obtaining a high level of engagement from process engineers to expedite the prototyping effort.

Design and component reuse allow leveraging of previous efforts in order to prevent "re-inventing of the wheel." When faced with unrealistic or unattainable deadlines, a decision to use existing components at a sub-optimal efficiency may be made in order to allow timely project completion. A successful completion of a prototype using such a strategy was able to demonstrate capability to the customer and allow the team to win a contract award. Later versions of the product would then contain newly developed components. Had the component re-use decision not have been made, prototype delivery would likely not have been timely, and the contract award would have likely been lost altogether.

Tailoring the test plan to allow for re-use of existing hardware and software has allowed great reduction of lead time in the past. Like component reuse, a tradeoff of using existing as opposed to developing new testing may positively affect the area of development time. Choosing to do this at the proper time, such as when time is limited and existing test protocols are able to provide sufficient results, is something that the MAF has done successfully in a few instances.

Another example that led to completion of prototyping activities under extreme time pressure involved extraordinary engagement from the process engineers during the prototyping process. An example described during an interview involved process engineers working extreme hours and weekends in order to expedite the prototypes through the MAF facility. As experts of the manufacturing process, the process engineers were able to ensure efficient development of the manufacturing process and the actual part production. By providing this amount of assistance, tight schedules were met with quality prototypes.

4.3. *The Proposed MAF Prototyping Process*

The MAF prototyping process refers to the sequence of actions that transform a customer's design, requirements, deadlines, and budget into a deliverable, such as a functional assembly or test data. MAF prototyping guidelines were produced and approved for use at the end of the internship and will be used going forward. The guidelines will be a living document such that they will be updated as improvements are developed. As defined by the guidelines, the prototyping process consists of the following groups of activities: Requirements and Planning, Non Recurring Expense Development, Part Procurement, Prototype Assembly and Test, and Customer Review, as shown in Figure 4.

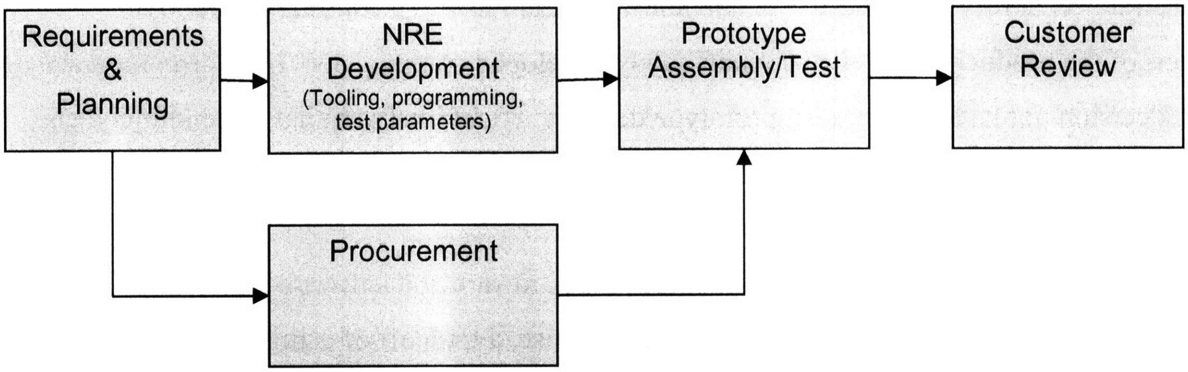


Figure 4: MAF Prototyping Process Overview

Within these groups, the tasks performed and the rigor with which each task is performed vary from prototype to prototype. Section 5 will discuss how the prototyping process should be tailored in order to include the proper tasks with the proper rigor to maximize customer value.

The first part of the process pertains to requirements and planning. The prototyping guidelines encourage early MAF involvement in the product development process for a number of reasons. First, the MAF will be able to gain an understanding of the primary factors that will drive the success of the prototyping effort, which will be used to tailor the prototyping process. Also, the MAF will be able to create a conceptual plan for developing the prototype concurrently with product design. Additionally, if involved up front, the MAF will be able to contribute to the producibility of the design which can increase the success of the project. Once the magnitude of the prototyping effort has been determined, a Statement of Work (SOW) and means of funding will be approved by both the customer and the MAF. The SOW will include technical requirements, scheduling, design details, and any other pertinent information that is required for the prototyping effort.

An execution phase of the process is made up of part procurement, non-recurring development, and manufacturing operations. Parts for prototypes are often supplied to the MAF by the customer. When this does not occur, the MAF may order the parts through informal engineering channels, or perhaps through the formal Material Requirements Planning (MRP) procurement method. Non-recurring development is a critical part of the prototyping process, during which assembly equipment is setup, programmed, and purchased if necessary. Also, assembly and test tooling is designed and developed, operator instructions are created, and testing and environmental screening programs are developed. The final part of the execution phase is the assembly and testing of the prototypes.

The last group of activities in the prototyping process is the customer review. The MAF will seek feedback from the customer with regards to their satisfaction with the prototyping effort. The feedback will be useful for improving the prototyping process for future efforts. Additionally, the MAF will inquire about the customer's future plans for the program in order to best prepare for future actions.

5. Tailoring the Prototyping Process

As mentioned previously in the literature study, a one size fits all approach does not exist when it comes to managing a process in product development. This thesis claims that the same holds true for prototyping processes. The context in which prototyping is performed varies greatly. For example, the stage of product development in which a prototype is produced is a major consideration when defining the context of the prototyping effort. Numerous prototypes may be produced throughout the development of a particular product. The context for each one of these prototypes will be different because new information will exist and desired outputs from the prototype will be different further in the process. In his manual on Product Development Value Stream Mapping (PDVSM), Hugh L. McManus (2005) discusses determining the scope of a definable process within the product development value stream, shown in Figure 5.

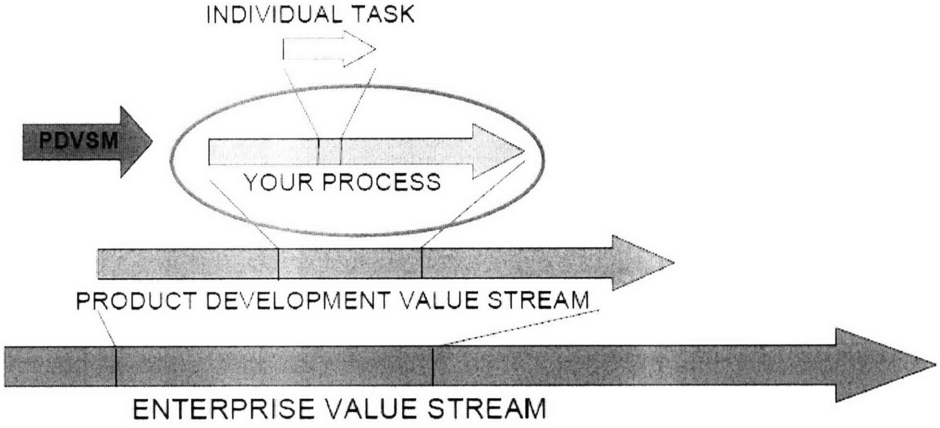


Figure 5: "PDVSM applies to a definable process within the product development value stream (Manus, 2005)"

Regarding prototyping, one can picture various prototyping efforts occurring throughout the product development value stream as shown above. Many of the processes will differ among these various prototyping efforts. However, there will be many tasks that are similar, if not identical. This thesis encourages defining a tailorable prototyping process which contains the universal tasks in addition to allowing selection of optimal variations for other tasks that best suit the particular needs for a given effort.

In addition to the context in which the prototype is created, the desired results and key objectives are prioritized differently for different efforts. Schedule deadlines may be a key driver in one effort, while optimal performance might be critical in another. It is important to have the capability to tailor the prototyping process in a way that best meets the specialized needs for a particular prototyping effort.

The framework utilized in this chapter occurs during a planning phase, which involves identifying a number of project characteristics. The prioritized goals of the customer, as well as other conditions regarding the context of the prototyping effort, are rated on a numeric scale. These numeric ratings can then be used to categorize the prototyping effort into an overall level of rigor, which will be discussed later in this section. Attributes, such as the tasks and features of the prototyping process, can be tailored based upon the level determined in this procedure. The tailoring involves adding or deleting tasks, or simply refining the level of rigor with which certain tasks are performed. While the framework provides only a baseline for tailoring the process, it will provide insight on the type of activities that align with the priorities of the customer and generate desired results.

5.1. Project Characteristics

A number of characteristics should be analyzed in order to determine the proper prototyping process to pursue for any given effort. These characteristics may be defined by the customer, dictated by the context of the project, or be based on a projection into the future. This section will discuss some of the important characteristics identified for the Microwave Automated Factories (MAF) at APC. Each characteristic will be rated on a scale of 1 to 3 based on criteria discussed further in this section.

5.1.1. Prototype Budget

Each development effort typically is given a budget. For activities performed at the MAF, the budget is typically quantified in a Statement of Work (SOW) as well as an inter-organizational transfer (IOT). Implications of running over budget, although typically monitored as one of two key metrics in the earned value management system (EVMS), often vary depending on the relative importance of other project characteristics. When determining the characteristic rating, projects with a relatively low budget and where cost is a key priority score low, and projects where the cost is a relatively low priority score high.

5.1.2. Prototype Schedule

Prototype schedule refers to the expected amount of time the prototyping effort should take. Typically, the schedule is dictated by a desirable completion date. Often times, the completion date is firm and must be met at all costs. A supplier down-select or contract award decision by the customer scheduled for a firm date is an example of a critical completion date. In a case such as this, if the prototype is not available for this decision, the project will be lost in its entirety. Projects such as these will be rated low. In other circumstances, the completion date may be more flexible and more easily delayed in order to achieve other prototyping goals. In these circumstances, the schedule rating should be high.

5.1.3. Desired Prototype Performance

The desired level of prototype performance varies greatly. Even within functional prototypes, the desired performance ranges from a low expectation of accuracy to fully certified production worthy performance accuracy. Performance expectations for prototypes in the proof of concept and other early phases might be completely unspecified, to be determined, or listed as "best effort", meaning that there is not a minimum requirement. Prototypes of this type are rated a 1 on the characteristic scale. However, other circumstances call for strict adherence to minimum performance standards. A prototype such as this will be rated a 3 on the characteristic scale. Typically, prototype performance expectations will reside within these two extremes.

5.1.4. Design Maturity

Design maturity is a key characteristic to consider when tailoring the prototyping process. With a less mature design that is likely to change, it will often be advantageous to use a relatively inexpensive approach with more flexible processes. However, with a mature design that will likely not involve significant changes, a more thorough development of the manufacturing process may be advantageous. The maturity of design will depend greatly upon the stage in the product development process, the degree of innovation involved in the product, and the risk associated with the design. Prototypes early in the development phase with many design changes expected in the future will be rated low on the characteristic scale, while prototypes in late stage development with few expected design changes will be rated high.

5.1.5. Process Production Readiness

Production readiness refers to the degree that the manufacturing process is capable of producing parts for full production. Full production readiness means that the process will support peak volume production rates and will provide the best available quality. Attributes that are considered when determining production readiness are the cost and time required to upgrade the manufacturing process for full production. Activities involved in this upgrade include production equipment and tooling development, machine and test programming, and creation and refinement of part procurement procedures. Processes that are ready for production are rated highly on the characteristic scale, while processes that are not expected to be used further in the project are rated low.

5.1.6. Process Maturity

The MAF considers process maturity as a measure of the producibility of a component or assembly. MAF personnel conduct process maturity evaluations in order to provide insight into the manufacturing process development and to identify risks involved in the project. The Process Maturity evaluation provides a basis for estimating manufacturing development costs and schedules, predicted output yields, and capacity estimates. Additionally, unproven technology is identified and highlighted in order to develop risk mitigation plans. The four main categories that are assessed are:

- Material Selection – The degree to which the MAF has worked with the chosen materials and the ease with which the materials are processed.
- Maturity of Process – The amount of experience that the MAF has had with the necessary manufacturing processes to be used.

- Equipment – The amount of experience that the MAF has with the actual equipment that will be used in manufacturing, or with similar types of equipment.
- Tooling – The amount of experience that the MAF has had with the actual tooling to be used or with similar types of tooling.

Projects early in the development cycle are likely to score lower on the process maturity evaluation, due to the introduction of new technology and innovative materials and designs. Lower process maturity levels are acceptable since there will likely be time to develop and refine the process as the product development process continues. Once projects are further along the development cycle, it is desirable to ensure higher process maturity, which in turn leads to preferable manufacturing results such as high throughput and high yields. For example, a new design may incorporate smaller bonding pads in order to reduce the footprint on a new design. Bonding to the smaller pad, however, provides a greater challenge to the process team. If the same equipment and processes are used for this more difficult task, it is likely to lead to lower yields (more defects). Therefore, the design will score lower on the process maturity scale. Low process maturity scores correspond to a lower characteristic rating, while higher process maturity scores correspond to high characteristic ratings.

The MAF distributes Producibility Design Guidelines to communicate the current capabilities of the equipment and processes in the MAF. It specifies preferred materials, geometry, and spacing for various different applications. By adhering to the guidelines, the design team is confident in the manufacturability of their design. However, innovation and technology advancements will often require design to deviate from the guideline specifications. When this occurs, the violations are stated and risk is assessed for each. When the risk is high, the program typically budgets to allow for resolution, as well as performing development studies, communicating the risk with the customer, and looking into the possibilities of redesign.

5.1.7. Purpose

Prototypes are produced for a variety of purposes. Information is generally the main purpose for prototyping, but the type of information desired will vary from prototype to prototype. The prototyping effort might be a proof of concept, a proof of design, or a proof of manufacture. The prototype may be used to generate internal knowledge, or it may be used to demonstrate capability to the customer in effort to win a business contract. Prototypes in the proof of concept stage are rated low on the characteristic scale, while proof of manufacture projects (often used for contract awards) are rated high.

5.1.8. Prototype End Use or Application

Often, the development team wants to gather information about the prototype in a lab setting. In this case, only the test relevant aspects of the prototype need to be functional. Prototypes such as these are rated low on the characteristic scale. Other times, the intent of a prototyping effort is to analyze how the prototype performs in the specific environment that the product will face in the field. An analysis such as this may be done through environmental testing or through actual trial use in application. During these studies, the prototype and the manufacturing process must be developed much more thoroughly such that a relevant assessment of the product can be performed. Prototypes in this category are rated high on the characteristic scale.

5.1.9. Prototype Quantity

The desired quantity of prototypes to be produced is an important consideration in part because the higher the quantity, the more emphasis that should be placed on reducing unit cost in relation to the development cost. Often, systems and arrays at the customer level may contain hundreds of each part that is produced in the MAF. As a result, high quantities may be required even during prototyping phases early in product development. The expected prototype volume itself, if high enough, can drive a decision towards a more rigorous prototyping process. Prototypes produced in low volumes are rated low on the characteristic scale, while prototypes produced in high volumes are rated high.

5.1.10. Future Development Path

The future development path takes into account the potential next steps of the program, the timing, and the probability of advancing to full rate production. If full rate production is expected, the projected production scheduling and volume is considered. Any additional information regarding the future of the program may also affect the prototyping effort delivered. Prototypes with no future plans are rated low on the characteristic scale, while prototypes with a high certainty of reaching production are rated high. A summary of the rating scale for each of the characteristics is shown in Table 1.

Characteristic	**1**	**2**	**3**
Prototype Budget	Relatively low, A key priority		Relatively high, Not the priority
Prototype Schedule	Fast delivery, Hard deadline		Longer lead time, Softer deadlines
Desired Performance	Best effort, No pass/fail criteria		Critical, Pass/fail criteria
Design Maturity	Early stage development, Many changes expected		Late stage development, Near final design
Process Production Readiness	Development unlikely to move forward		Ready for production volumes
Process Maturity	Low		High
Purpose	Proof of concept		Proof of manufacture, win contract award
Prototype End Use/Application	Lab/Internal use		Use in actual environment, customer use
Prototype Quantity	Few (1-5)		Many (100+)
Future Development Path	No future expected with current design		High certainty of full production

Table 1: Prototype Characteristics

5.2. Prototyping Levels

In most cases, commonalities exist when tailoring process attributes which allow classification within three levels. By classifying by level, communication of requirements can be conducted more smoothly. Although there will almost always be exceptions, which should be communicated clearly, general guidelines for three levels of prototyping are described below. Generally speaking, the level of prototyping corresponds to the average ranking of the characteristics shown above. The descriptions are only general guidelines, as all requirements will be defined in the SOW.

Level 1 – This prototype is typically intended to demonstrate a concept relatively early in the design process. The end use of the prototype is usually in a lab setting within Raytheon. Additionally, prototypes of this level are typically built in low quantity, with no future production prior to significant design change. A prototyping effort at this level does not place emphasis on design to cost or design for manufacturing/assembly. NRE efforts are not guaranteed to generate production worthy materials.

Level 2 – A prototype at this level is typically intended to test critical parameters. The prototype might be shipped to an external customer. However, the units are to be used for evaluation only and will have known limitations. At this level, prototypes are typically produced in low to medium quantities. Moderate design change is expected prior to potential production. Some emphasis will be placed on design to cost or design for manufacturing/assembly, and it is possible that some of the NRE effort may be carried forward to production.

Level 3 – This prototype is typically intended to meet mature specifications and possess nearly full functionality. The prototype may be field tested and rolled out in deployment. Prototypes at this level are built in medium to high quantities, and production is anticipated with minimal changes. However, if design changes considerably, NRE invested may be lost.

Figure 6 displays the relationship between prototype cost and schedule with production readiness. Although prototype lead time and cost are greater at higher prototype levels, future time and expense to transition to production are lower.

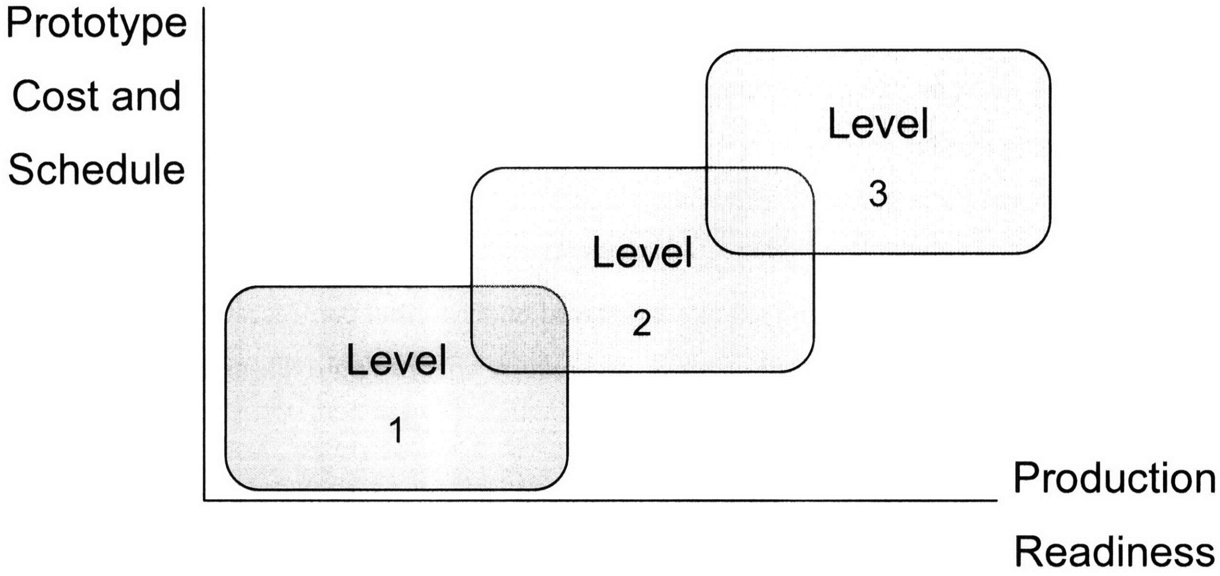


Figure 6: Prototype Levels

5.3. Process Attributes

A number of tasks are performed throughout the prototyping process. The particular tasks that are performed, as well as the rigor in which the tasks are performed, should vary from project to project. These attributes are typically tailored such that they correspond with the ratings of the characteristics and the prototyping level. While the average score for the characteristics provides a general baseline for the attribute level, particular characteristics or other factors will often override the average and drive a particular attribute to a certain level. Judgment should be used when tailoring the attributes. The characteristics ratings are useful in guiding these decisions, but they are not independently sufficient. Some of the key tasks will be described in this section, with a particular focus on the aspects of the task that will vary depending on the type of prototype desired. Additionally, corresponding ratings will be given for the attributes.

5.3.1. Requirements and Planning

The level of documentation and artwork control will vary depending on the level of rigor appropriate for a given prototyping effort. The MAF acknowledges the following types of configuration control for engineering documents and data:

- **Engineering Sketch:** not required to have specific format, the drawing shall completely describe the item, the design engineer is responsible for configuration control and shall maintain a master document and is responsible for disseminating copies, the engineer shall approve changes to the drawing which shall be incorporated before dissemination (low attribute rating).
- **Formal Release:** These documents are placed under formal configuration control, contain full traceability of all changes, and require change approval (high attribute rating).

5.3.2. Procurement

The parts procurement for prototyping can be done in a number of ways. Often times, the customer will provide the parts that they wish to be assembled directly to the MAF. When this is not the case, the MAF will procure the parts either through formal channels such as MRP or through informal channels such as engineer direct orders. Use of the MRP system provides the benefit of comparing quotations, leveraging buyer power, and facilitating re-order procedures. However, initial implementation into MRP often requires time and effort, which may not be practical for low volume prototyping needs. Informal channels primarily are made up of direct orders from engineering to the suppliers. This procedure usually requires little time and can be beneficial for low quantity, one time builds. However, Raytheon will not be able to leverage buyer power or ensure the selection of the best supplier. Additionally, parts ordered in this manner are typically not directed through the incoming parts inspection, and are not approved for production use. The formal channels are rated high on the attribute scale, while the informal methods are rated low.

5.3.3. Process Method

Prototype production ranges from manual assembly performed by highly trained technicians (attribute rating of 1) to use of fully automated equipment with highly defined processes (attribute rating of 3). Manual processing provides the benefits of great flexibility, quick modifications, and trial and error with low associated costs. Typically during prototyping, a combination of automated and manual processes will be used. Tasks that are relatively stable and consistent with other products can be performed on equipment with little development. Meanwhile, tasks that are new and undeveloped can be performed manually. When late in the product development cycle, it is advantageous to perform the majority of the tasks with an automated process in order to increase the repeatability of the processes and to refine the manufacturing process to be used during the production phase of the product.

5.3.4. Tooling Development

Machine and test tooling will vary depending on the characteristics of the prototype. Tooling can be retrofitted or borrowed from other applications in order to provide a cost effective alternative. Temporary and non-robust tooling may be created for efforts that are not critical and long tool life is not necessary. These short term tooling solutions are rated low on the attribute scale. Robust production worthy tooling may be used for critical processes or for mature designs where the tooling is expected to be used in future builds. Tooling of this type rate high on the attribute scale.

5.3.5. Test Requirements

The purpose and context of the prototype will determine the requirements for testing. Due to long and expensive development of test programs, re-use of existing programs will be used when available. The amount of new test development depends on the purpose and importance of the testing. Prototypes that will be used in the field will need to be tested much more critically than proof of concept prototypes that are developed solely for informational purposes. In the case of the former (high attribute rating), it will often be necessary to develop new testing in order to perform the adequate inspections. Additionally, hardware correlations may be required to ensure test results are consistent, and software validations may be needed to ensure the correct feature is tested and that the data is valid. However, in the case of the latter (low attribute rating), it may be appropriate to leverage existing programming as much as possible to limit the cost and schedule requirements.

Development and re-use of test equipment follows much the same pattern as the programming software. Projects with less critical applications may best be suited for retrofit on existing equipment. However, the more critical the application and purpose of the prototype, the higher necessity to acquire the proper equipment regardless of reuse availability.

5.3.6. Process Control

Operator instructions, quality inspections, and component tracking systems vary in rigor for various prototyping efforts. Operator instructions range from very informal documents that travel with the parts throughout the process to formal documents located at each station that are approved and controlled through a documentation control system. Quality inspections are typically performed throughout a manufacturing process. The rigor of these inspections for prototyping will vary depending, upon other things, the importance of performance and the end use of the prototype. The MAF has full pedigree tracking capabilities, meaning that full component traceability is feasible for each of the parts assembled in the MAF. However, there is a substantial investment in resources to develop this capability. Some prototypes will utilize only manual component tracking, consisting of manual labels and tracking, in order to avoid the investment. Prototypes with higher process control will have a higher attribute rating. A summary of the attributes is shown in Table 2.

Activity	Level 1	Level 2	Level 3
Requirements and Planning			
Expectation for Document Control	Engineering Sketch	Engineering Release	Formal Release
Enforcement of Producibility Guidelines	Loose adherence to MAF producibility design guidelines and packaging requests.	Strong adherence to MAF producibility design guidelines and packaging requests.	Nearly full adherence to MAF producibility design guidelines and packaging requests.
Procurement			
Procurement Method	Customer supplied or procurement through Engineering Procurement	Customer supplied parts, Engineering Procurement or MRP	MRP; typically ordering same parts as needed for production.
Incoming Quality Inspection	None	Optional	Full
Non-Recurring Development			
Process Automation	Limited	Moderate	Mostly; if appropriate
Equipment Setup/Programming	Limited equipment programming, limited quality validation, little to no process development	Moderate equipment programming, moderate quality validation, minor process development.	Extensive equipment programming, extensive quality validation, and extensive process development.
Tooling Development	Resourceful reuse of existing tooling, limited functionality, and short lifetime.	Moderate functionality with moderate lifetime. In most cases, tooling is not intended to be used during production phase.	Robust, long-life tooling is developed with extensive functionality; ideally production phase tooling.
Operator Instructions	Informal	Informal or Formal	Formal
Test Development	Primarily existing test equipment hardware and software	Existing test equipment hardware, limited software development	Potential new test equipment, extensive test development effort, Test result correlations and software validations are likely.
Assembly and Test			
Floor Control System	Process Engineering Control	Process Engineering Control	Production Control
Assembly	Special manual build	Build on prototype equipment	Build on production equipment

Table 2: Prototype Attributes

5.4. Performance Measures

The primary performance measures for prototyping efforts are cost, schedule, performance, and process production readiness. These four categories were defined in section 5.1. Theoretically, the ideal prototype will be low cost, short lead time, with top performance. Furthermore, in the ideal scenario, the manufacturing process will be prepared for production at the completion of the prototyping effort. In reality, tradeoffs exist between these four metrics. For example, in order to achieve higher levels of prototype performance, higher costs and longer schedules are likely to occur. Creating production ready processes will likely lead to increased up-front costs and schedules. In order to maximize customer value, priority amongst these metrics must be determined with the customer. As discussed, by determining priority up front, this information can be used as a project characteristic to shape the prototyping effort to best achieve the desired results.

5.5. Other Recommendations

As discussed earlier in the document, while working with a number of people within Raytheon, particularly within the MAF, I compiled best prototyping practices into a Raytheon document entitled the "MAF Prototyping Guidelines". In addition to tailoring the prototyping process, there are a few other recommendations listed in the guidelines that may help to add value to the prototyping process. Major recommendations, a few of which are listed in the guidelines, are described below. The recommendations are including MAF personnel early in the design phase, leveraging lessons learned, and communicating the implications of scope creep.

5.5.1. MAF Presence in Early Design

In a number of projects, particularly designs that are developed at remote locations, the process team from the MAF is not involved up front in the design process. Instead, near completed designs are submitted to the MAF with little room for future input. This procedure contrasts with Raytheon's Integrated Process Team approach, where representatives from numerous departments, including process engineering, are involved throughout the development process. Involving process personnel up front invites contributions towards producible design and allows for informed decisions regarding when to leverage a current process or design as opposed to a new innovation. These contributions will lead to more producible design, which will lead to higher levels of success. Naturally, the input from the process engineer may be overridden, such as cases when the addition of a new technology out-weighs the benefits of a proven, producible design.

5.5.2. Leverage Lessons Learned

The projects I witnessed at the Advanced Products Center typically captured a list of lessons learned, including challenges that the team faced and overcame. However, this file was stored on the project team's shared drive and there were no plans to incorporate them into a collective list. Raytheon supports and encourages learning from experience. Lessons Learned is a required task in Raytheon's stage gate process and it is taught as part of Raytheon Six Sigma. However, I feel that most of the lessons learned are kept at the team level, which prevents more profound learning at an organization level. A robust method for collecting and incorporating these lessons learned may help to improve processes at the site and division level. With this practice, teams leading future projects can leverage knowledge captured during previous projects in order to avoid reinventing what has already been done and prevent repeating the same failures that occurred previously.

5.5.3. Communicate Implications of Late Requirements and Scope Creep

APC goes to great lengths to increase customer satisfaction. While making great strides to accommodate the needs of the customer, APC is sometimes vulnerable to allowing late changes that may greatly affect cost and schedule. In effort to please the customer, the APC team takes pride in meeting the new requirements. However, late changes are one of the key contributors to budget and schedule slips, as found when analyzing project schedules, reviews, and summaries.

A common saying in management is that "you get what you measure". The traditional development metrics, cost performance index (CPI) and schedule performance index (SPI), do not highlight requirements volatility and changes of scope. In order to remedy this performance measurement inefficiency, the Raytheon Six-Sigma team is rolling out Technical Performance

Measures (TPMs). TPMs identify "to be determined" (TBD) requirements and requirements volatility (changes in requirements) and show the effect that they have on performance yields. Additionally, changes in scope are tracked and their effect on the project is quantified. Due to the sizeable impact that these factors have on a prototypes success, it is recommend that these metrics be fully adopted in the product development process.

5.5.4. Develop Trade-off Sheets for Major Prototyping Activities

Much like Toyota does for evaluating potential failure modes, Raytheon can use trade-off sheets to evaluate prototyping decisions. The effects of time and schedule can be charted against various levels of rigor for the main prototyping activities. By doing so, the project team can communicate the implications of requirements with the customer, quickly generating estimates for cost and schedule. Likewise, the team can quickly evaluate tradeoffs and decide on optimum decisions to extract the most value from the prototyping effort.

In order to generate the trade-off curves, historical data and empirical data should be collected for a number of the primary activities, similar to what is described later in this thesis, and charted. On the horizontal axis, various levels of rigor for a particular activity will be shown. On the vertical axis, corresponding lead times and costs will be mapped. The resulting curves will show the relationships.

5.6. Schedule Implications at the MAF

A number of metrics are affected by the decisions made during the tailoring of the prototyping process, as discussed previously. Delivery schedule is one of the key determinants of customer satisfaction. The complexity of the product being designed and prototyped has a major influence on the delivery schedule, regardless of prototype level. However, within a certain product complexity, the level of prototyping will further influence delivery schedule. A brief summary of the implications that attribute and prototyping level choices have on schedule is included below. Prototyping steps mentioned are tooling development, assembly programming and instructions, part procurement, assembly processing, test planning and development.

As mentioned in the Methods section, a baseline was difficult to obtain based upon historical data. Although timing for discrete activities was not available for historical projects, I was able to obtain empirical data from a number of experts for the majority of tasks at each prototyping level. Comparing this data among activities at each level allows understanding of the implications and gains achieved from properly tailoring the prototyping process.

Although it is difficult to provide precise values, the sections below give some insight on the implications that prototyping decisions have on prototype delivery schedule. The need for developing new test programs, formal procurement procedures, assembly programming, and others are examined during the project characteristics phase and weighed against the importance of delivery schedule. The process attributes are determined based upon this analysis, as discussed previously.

5.6.1. Schedule Implications on Tooling Development

The type of tooling that is used for prototyping will vary depending upon the prototyping level. For Level 1 type prototypes, there is great incentive for resourceful reuse of existing tooling since the expected lifetime of the tooling is quite short. As the prototype level increases, so does the lifetime expectance of the tooling. Therefore, more robust tooling will be necessary.

The tooling schedule impact resides mainly on whether or not new tooling must be designed and fabricated, as well as the complexity of the tooling. The higher the level of prototype, the less likely appropriate tooling will be available for retrofitting. The complexity of the tooling will be driven mostly on prototype complexity rather than prototype level, although higher prototype levels may require more tooling functionality. Tooling that can be reused can be prepared in less than a day, while design and fabrication of tooling can take many weeks in some circumstances.

5.6.2. Schedule Implications on Assembly Programming and Instructions

Assembly programming and instructions typically take longer to develop the higher the prototype level. Level 1 prototypes generally employ more manual processes, use informal operator instructions, and require minimal quality validation. Level 3 Prototypes are likely to involve extensive equipment programming on automated equipment, potentially involve sophisticated software loaded operator instructions, and require extensive quality validation. The estimated time frame for programming and instructions on Level 1 prototypes is 1-2 days, Level 2 is 1-3 days, and Level 3 is 5-10 days.

5.6.3. Schedule Implications on Part Procurement

Part procurement has many stages, depending on the formality of the process used. Steps that might be performed include request for quotes (RFQs), vender quoting, negotiation, management approvals, placing purchase orders, vendor production, shipping, quality inspection, and part kitting. The formal procurement procedures, likely to occur on Level 3 prototypes, likely include all of these steps. Three to four weeks may be required to complete the listed tasks prior to vendor production. Vendor production time depends primarily on the complexity of the part and has tremendous variability. The quality control and kitting upon receipt of the parts may take up to two additional weeks.

Informal procurement methods may allow some of the steps listed above to be bypassed or expedited. Rather than performing a full blown quoting process, engineers may informally procure parts from suppliers and have the parts delivered directly to their attention, bypassing the incoming part inspection and kitting process. As a result, parts may be procured 6 weeks earlier than with the formal method. This approach can be beneficial for a one time order, but it would become burdensome for repeat orders. The formal process allows for replenishment of parts systematically, which will be necessary once the parts go into production.

5.6.4. Schedule Implications on Assembly Processing

The complexity of the design is the major factor in processing times for assembly. Level 1 prototypes typically involve manual component placement with minimal quality validation, while Level 3 prototypes generally are automated and contain extensive quality validation. Ranges provided for the processing at each of the three levels are 1-3 days for Level 1, 1-5 days for Level 2, and 3-10 days for Level 3.

5.6.5. Schedule Implications on Test Planning and Development

Test development is a major task in the prototyping process. Whenever possible, existing test equipment and software code is re-used. On Level 1 prototypes, there is less schedule and budget room for extensive program development, so more effort is put into re-use. Development of this type range from 3 to 10 days. Level 3 prototypes often provide more opportunity for development and will allow for the expense and time requirements of developing new test protocols. Activities that may take place include acquiring new equipment, extensive hardware and software development, database creation, and correlations and validations. Efforts such as this can range between two months and a year.

6. Conclusion

The main objective for prototyping at the MAF, as in any prototyping effort, is to get the most value out of the opportunity. Value may be thought of as information, performance, displaying production readiness or proving capability for the amount of resources consumed and time required. The extents to which each of the aforementioned variables add to customer value differ from project to project. Therefore, it is important to understand what the customer values most in the effort and act accordingly by modifying the process to best achieve the prioritized results. The intent of this thesis is to provide a means of tailoring the process to best achieve customer value given the characteristics of the project.

Achieving customer value in the prototyping process is critical to APC's business because it is likely that the customer will bring production into the MAF, thereby improving business financials. Misalignment with customer expectations will be avoided by tailoring the process around the metrics that the customer prioritizes. Confusion and inconsistency will be limited by having a clear and understood process.

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